Run 2b meeting: update on Recycler Electron Cooling

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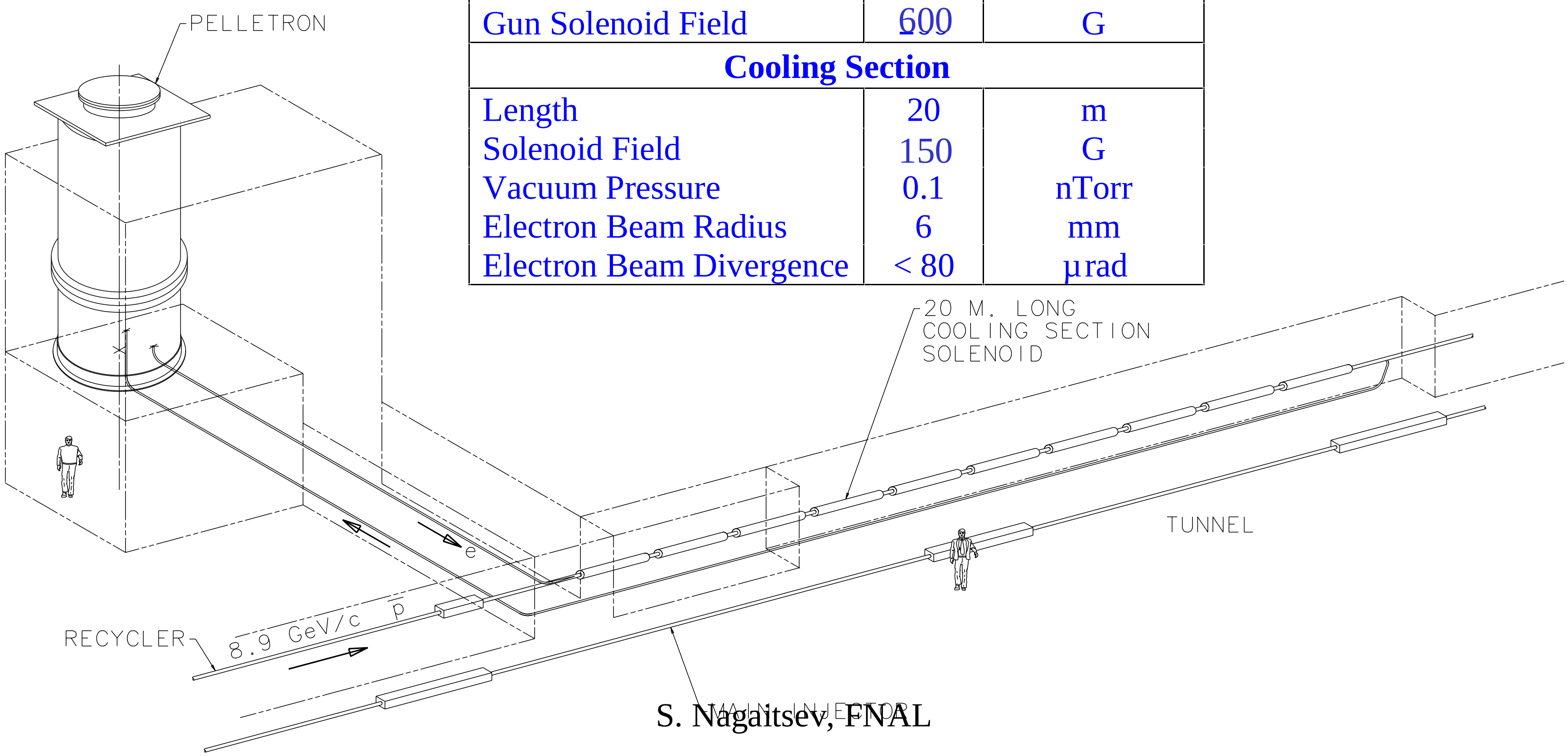
October 23, 2001

Schematic Layout of the Fermilab's Recycler Electron Cooling

Electron Cooling System Parameters

Parameter	Value	Units
Electrostatic Accelerator		
Terminal Voltage	4.3	MV
Electron Beam Current	0.5	A
Terminal Voltage Ripple	500	V (FWHM)
Cathode Radius	2.5	mm
Gun Solenoid Field	600	G
Cooling Section		
Length	20	m
Solenoid Field	150	G
Vacuum Pressure	0.1	nTorr
Electron Beam Radius	6	mm
Electron Beam Divergence	< 80	μrad



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The electron cooling scenario considered in 1998-99 as part of the CDR.

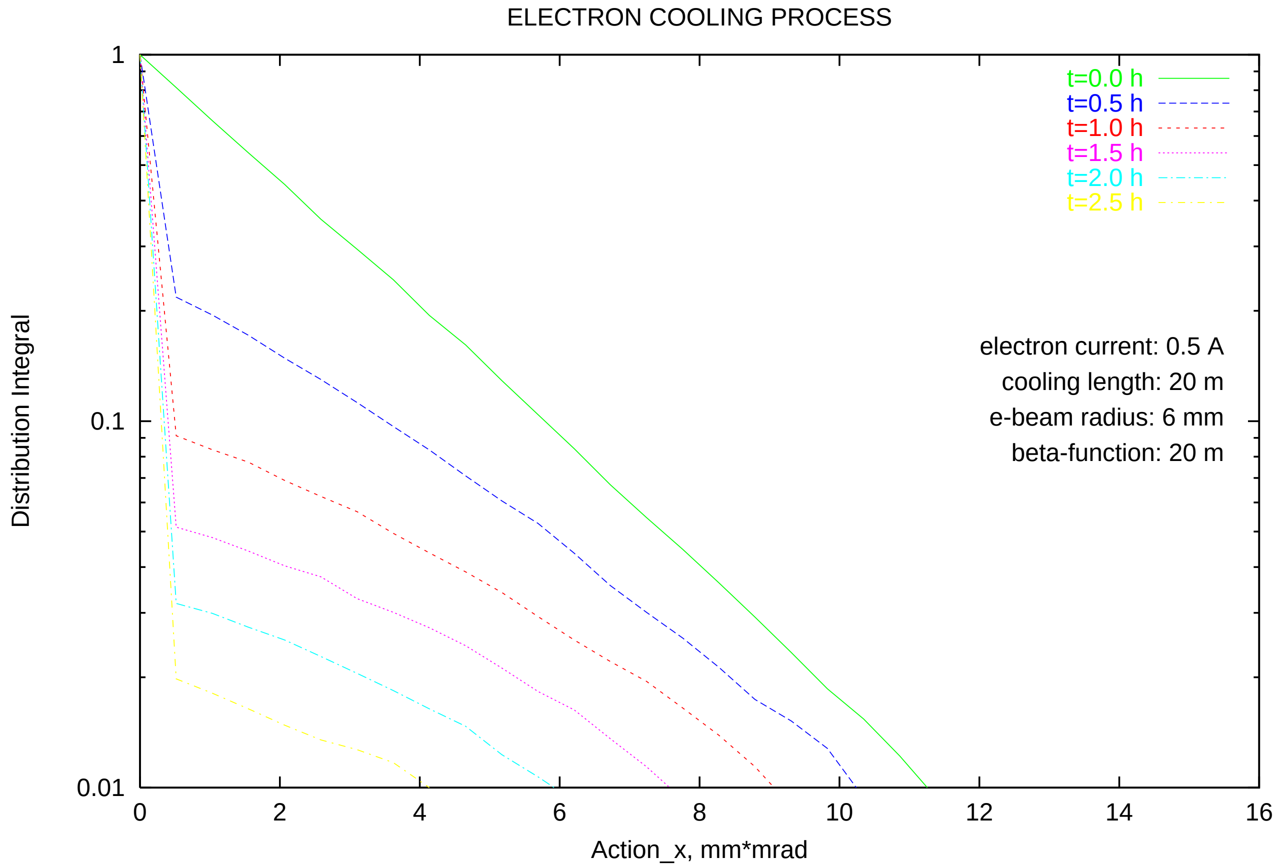
1 "Hot" antiprotons arrive at the Recycler: 2.5-10x10^{12} pbars, 400 eVs, 30 π mm-mrad (n, 95%). Transverse stochastic cooling starts and cools pbars to 15 π mm-mrad in two hours.

2 Every 15 minutes a new portion of pbars arrive from the Accumulator: 10^{11} pbars, 10 eVs, 15 π mm-mrad.

3 After two hours of stochastic cooling the transverse emittance is reduced to 15 π mm-mrad. Electron cooling starts.

4 After 3 to 8 more hours of continuous transfers from the Accumulator we end up with a stack of: 150 eVs or less, 10 π mm-mrad or less.

Evolution of the transverse emittance



Initial distribution: gaussian with a 15 π mm-mrad (n, 95%) emittance

Initial cooling rate for a 15 π mm-mrad beam: 6 π mm mrad/hr

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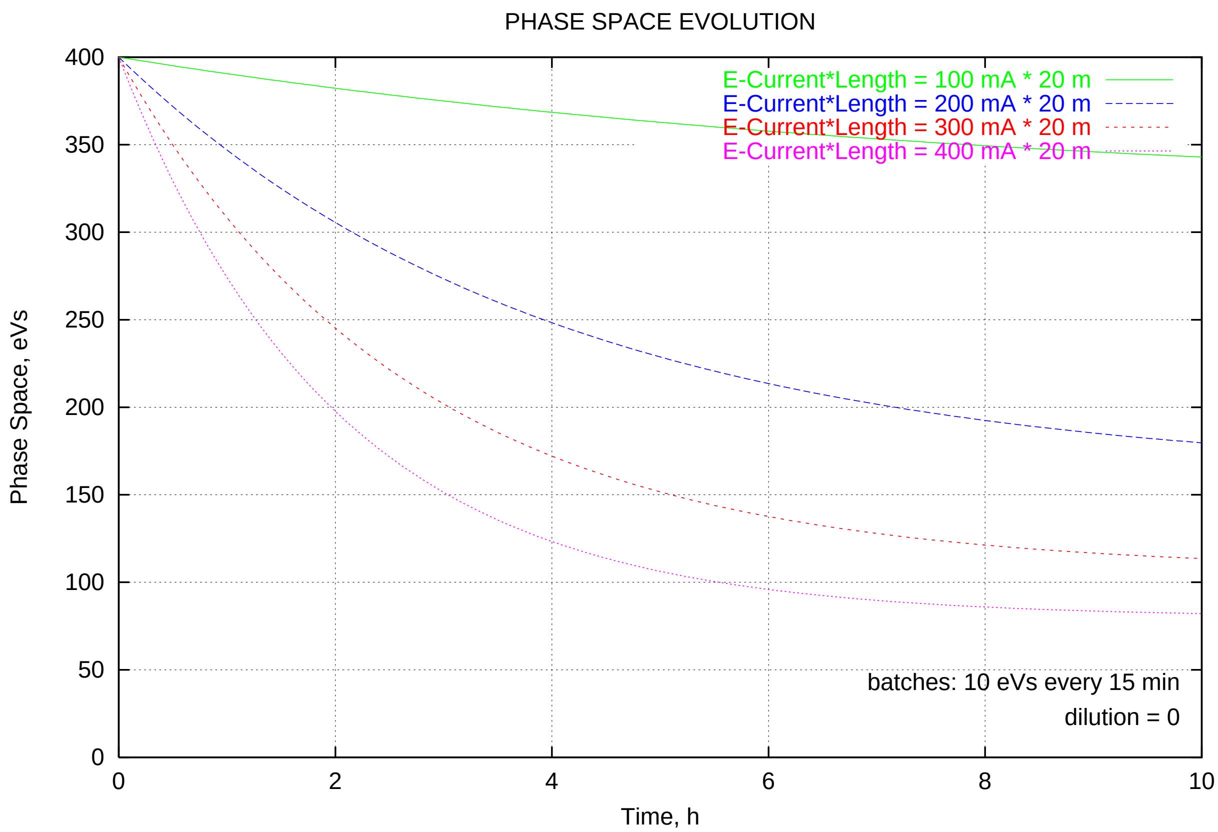
Evolution of the longitudinal phase-space area



Current electron cooling system design is optimized for the longitudinal cooling. The efficiency of the long. cooling depends primarily on the frequency of transfers from the Accumulator and the effect of these transfers on the stack emittance (should be <1% increase).

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Electron Cooling R&D
Project Goals

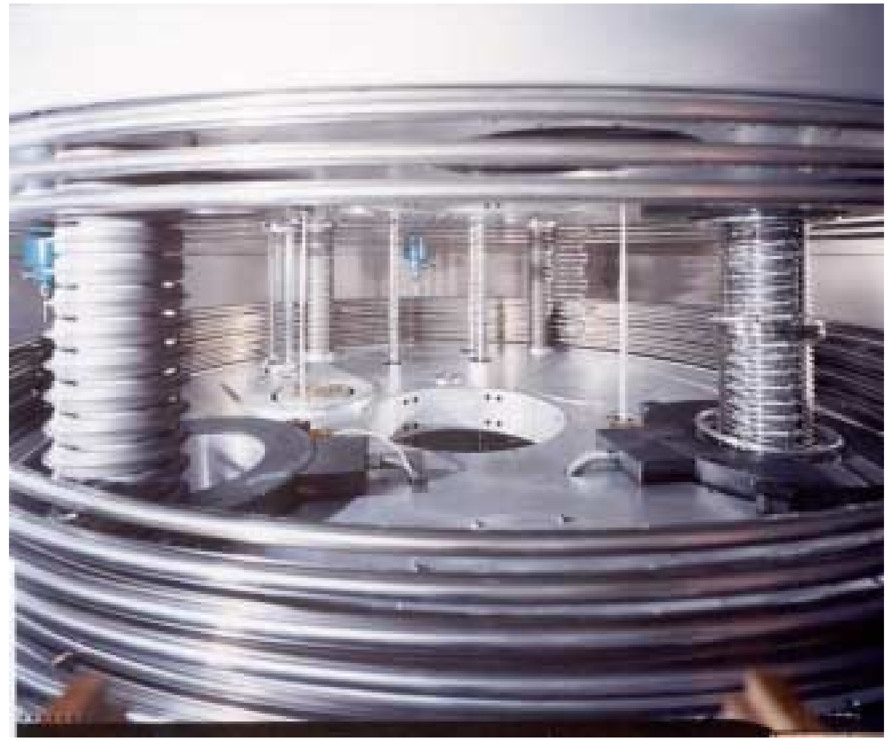
• Electron beam current	0.5 A
• Electron beam kinetic energy	4.3 MeV
• Beam angular spread (cooling section)	80 μrad
• Energy spread (FWHM)	500 eV
• Pressure (cooling section)	1×10^{-10} Torr
• Typical time between beam “crashes”	1 hour
• Crash recovery time	5 min
• Typical time between tank openings	1 month (initial)
	6 months (final)

Project issues to be covered in this talk

- Pelletron commissioning and beam recirculation tests
- Beam line elements
- Beam diagnostics
- Cooling section solenoid
- Installation plans

Fermilab Electron Cooling R&D Facility

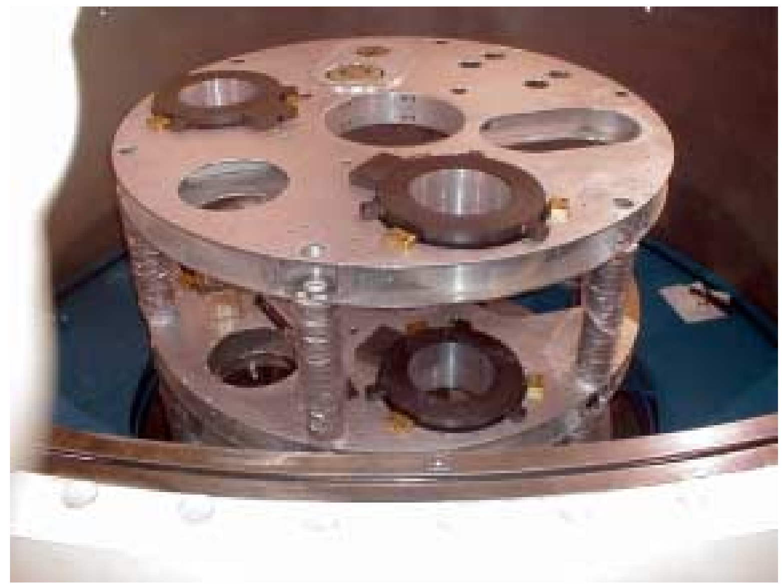
5 MV Pelletron installed



High-voltage column with grading hoops partially removed to show the accelerating tube (right) and the charging chains (far center).

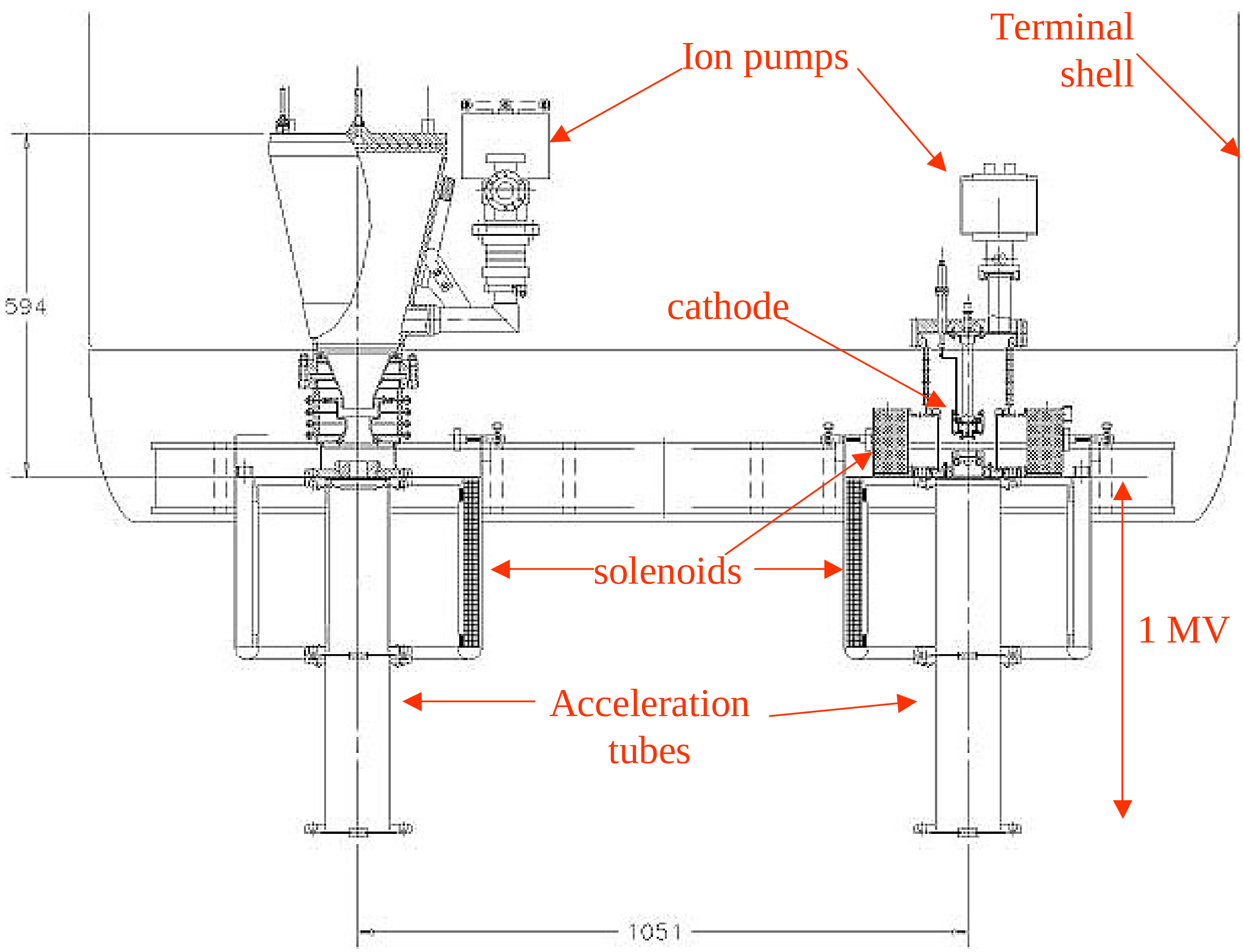
Fermilab Electron Cooling R&D Facility

The Pelletron tank is accessed through a manway.



Structure inside the tank -- separator boxes and beam lenses. No beam tubes were installed at the time of this photo.

Electron gun and collector assembly



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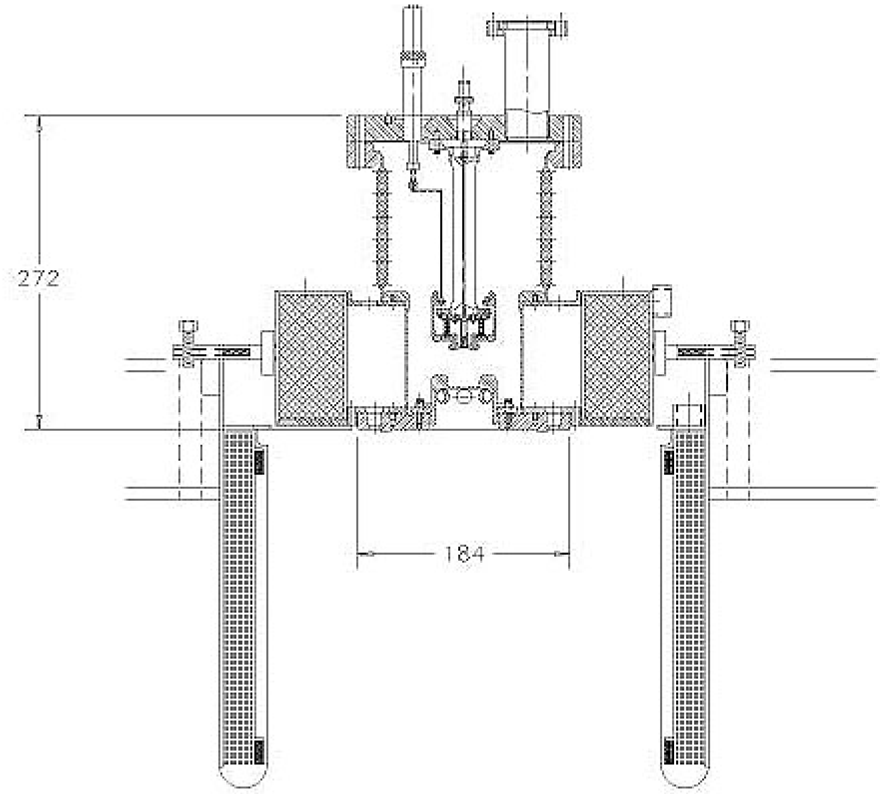
Electron Gun



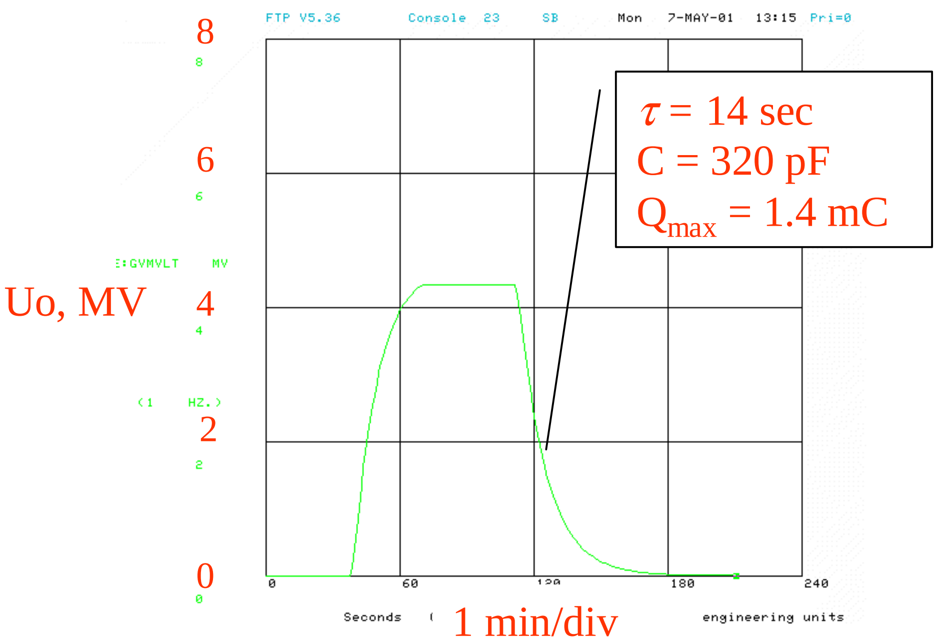
Gun assembly with solenoids

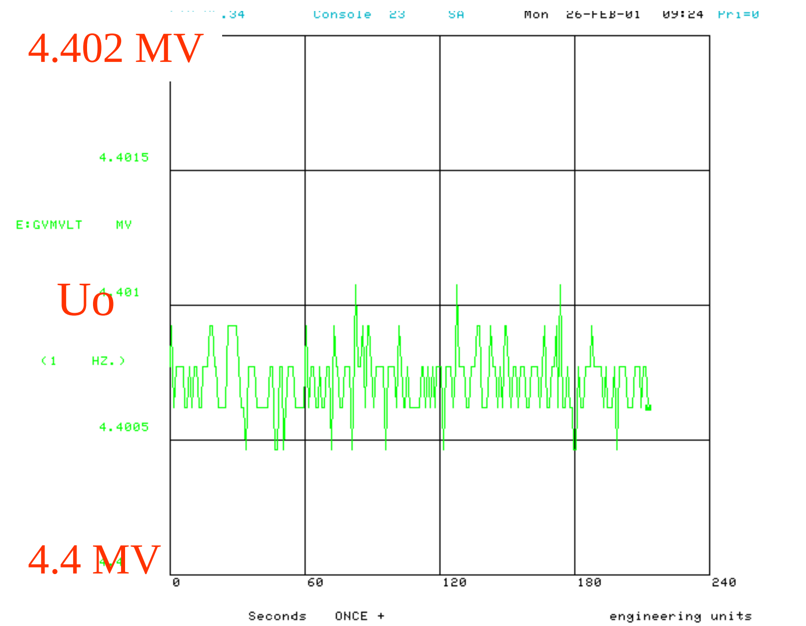
Cathode assembly mounted on a 200 mm OD flange.

Pelletron commissioning

- The 5 MV Pelletron has been installed and commissioned. While filled with SF_6 (no vacuum tubes) at 5.5 atm the Pelletron reached more than 6 MV, thus, no HV problems on the gas side are expected.
- Because of the large amount of energy (3 kJ) stored in the HV terminal and its potential for damage, the HV conditioning of vacuum tubes is performed with the help of shorting rods, one 1-MV section at a time. Each section (out of 5) was conditioned separately to 1.2 MV. The Pelletron with tubes was then conditioned to 4.8 MV. The Pelletron design voltage of 5 MV has not been demonstrated yet. The manufacturer will replace the ceramic accelerating tubes to fix the problem.
- Overall, the Pelletron PO is still incomplete due to several outstanding items (voltage, controls, cooling, documentation) that do not meet the performance criteria. The last 10% invoice has not been paid yet.

Charging and voltage regulation

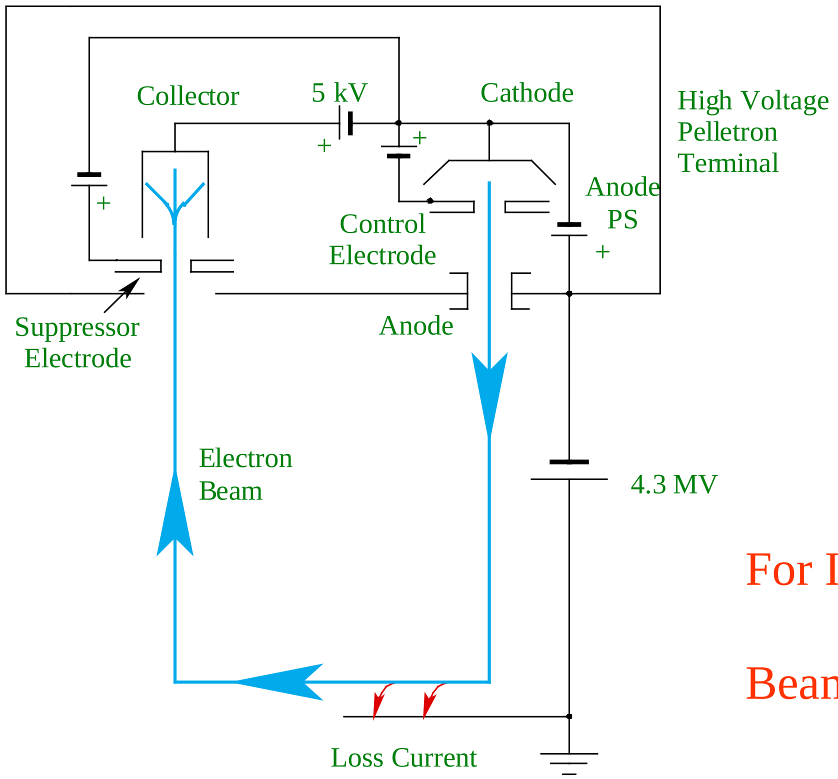




Pelletron charging with a voltage regulation system ON. After about 1 min the charging system was turned OFF and the terminal was discharged through resistive dividers.

Terminal voltage in a regulation regime: 500 V/div, 1 min/div. Required voltage for the Recycler cooling: 4.36 MV.

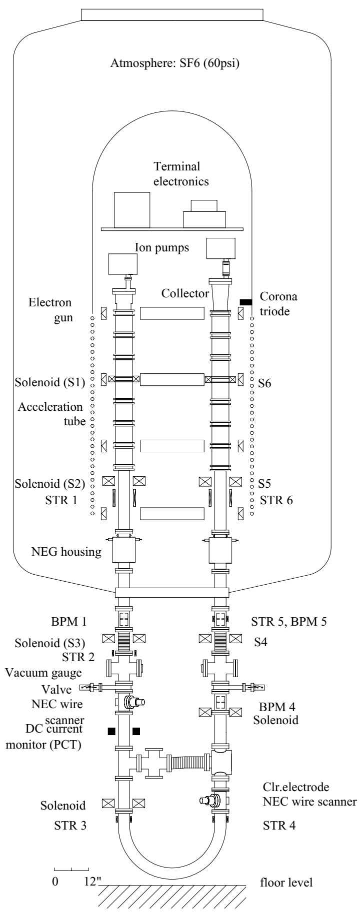
Simplified schematic of beam recirculation



For I= 0.5 A, ΔI_{loss}= 5 μA:

Beam power	2.15 MW
Current loss power	21.5 W
Power dissipated in collector	2.5 kW

Electron Cooling Proof-of-Principle
(Recirculation experiment)



GOAL

- To demonstrate a 0.2 A recirculation for 1 hour using an existing 2 MeV Pelletron at NEC

HISTORY

Nov. 95: project started

Jan. 97: first recirculated current (10 μA)

May 97: new gun and collector are installed

Dec. 97: Max. recirculated current of 0.2 A

May 98: 0.2 A for 1 hour

Sep. 98: 0.2 A for 5 hours

Dec. 98: Max. current of 0.7 A

Jan. 99: Gun solenoid (200 G) installed

Feb. 99: 5 MeV Pelletron ordered

May.99: 0.9 A with 200 G at the cathode

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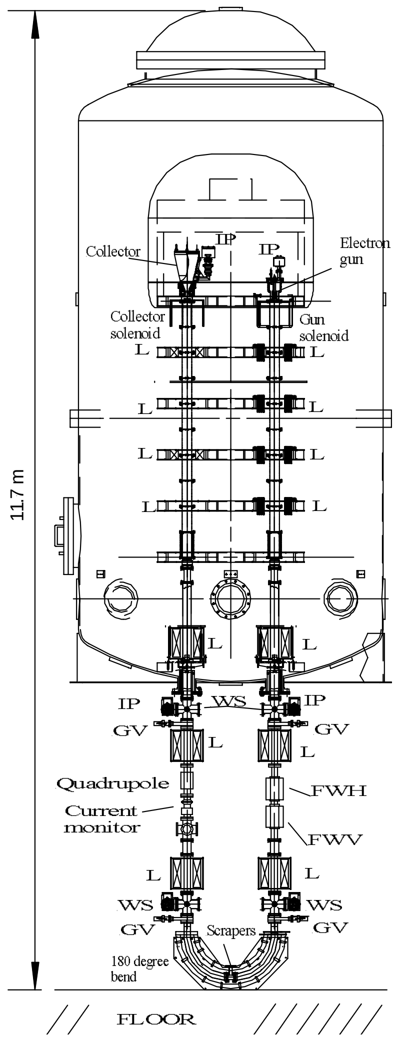
Electron Cooling R&D Facility at WideBand
(Recirculation experiment)



GOAL

- To demonstrate a 0.5 A recirculation for 1 hr. at 4.3 MV

HISTORY

Feb 99:	5 MV Pelletron ordered.
Jun 00:	Pressure tank installed at WideBand.
Dec 00:	Tank at 80 psig, 5 MV tests without vacuum tubes.
Feb 01:	Gun-side vacuum tubes installed and tested.
Mar 01:	Collector-side tubes installed. Operations began.
Apr 01:	Beam permit issued. All components in place.
May 01:	First beam of 30 μA in the collector at 4.3 MV.
July 01:	Reached 10 mA, HV conditioning is very unstable, tubes do not behave properly.
Aug 01:	Switched to operations with 3.5 MV. Routine conditioning to 4.3 MV.
Oct 01:	Reached stable 100 - 150 mA beam.

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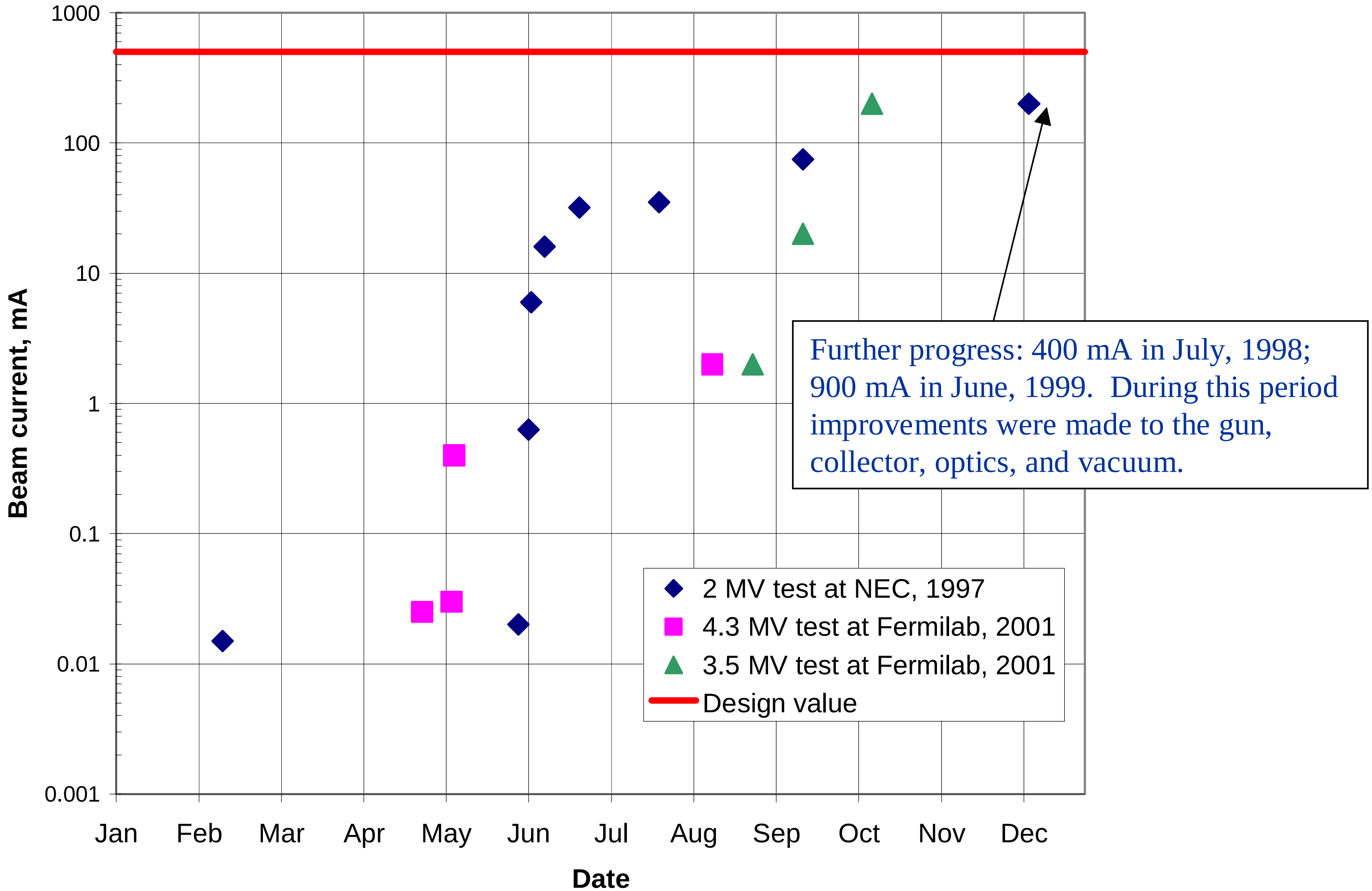
Attained stable (1 min.) recirculation currents



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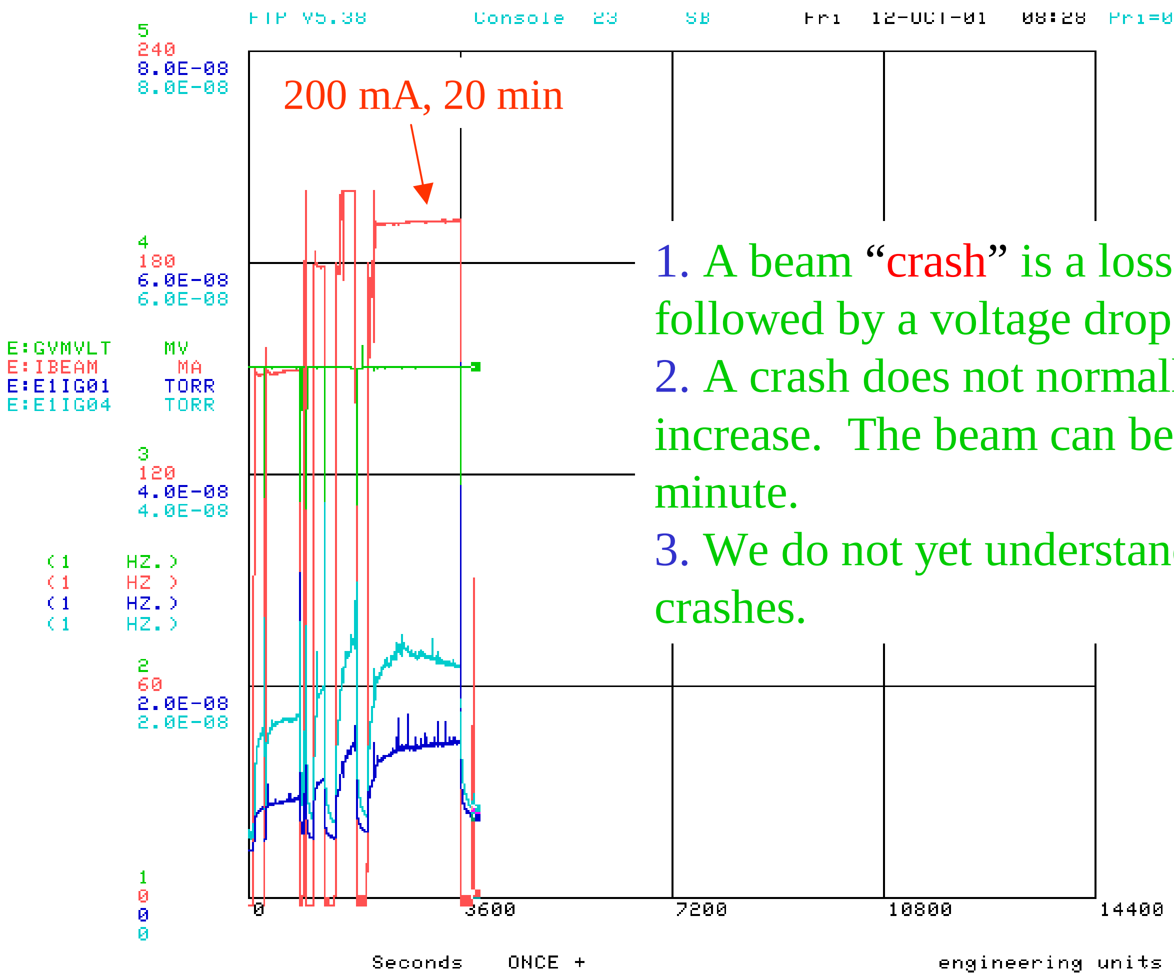
What determines the rate of progress in beam current and beam stability?

- Duty cycle of machine operation
- Operator learning curve
- Vacuum outgassing with beam
- Beam physics

- Duty cycle of machine operation
  - HV voltage sparks can damage electronics in the terminal. A typical shutdown for repair is one week, minimum two shifts (if one has a spare part). All of the Fermilab-supplied components have been well protected (thanks to G. Saewert and his EE colleagues) and are now very reliable.
  - HV voltage sparks de-condition the vacuum tubes. Currently, we operate at 3.5 MV with HV conditioning being kept at 4.2 MV. To operate at 4.3 MV it is essential to condition the tubes to 5 MV. The present tubes do not allow us to operate at 4.3 MV without spending a lot of time conditioning.
  - Some violent vacuum break-downs release a lot of gas. One can not operate above 1-2x10^{-8} Torr and has to wait for the vacuum to improve. This was very typical after opening tubes to air. The frequency of such events diminishes with time. Good HV conditioning also helps.
- Operator learning curve
  - We operate 5 days a week, two 6-hour shifts. There are 10 people on the crew list, 8 are fully capable of operating the machine.

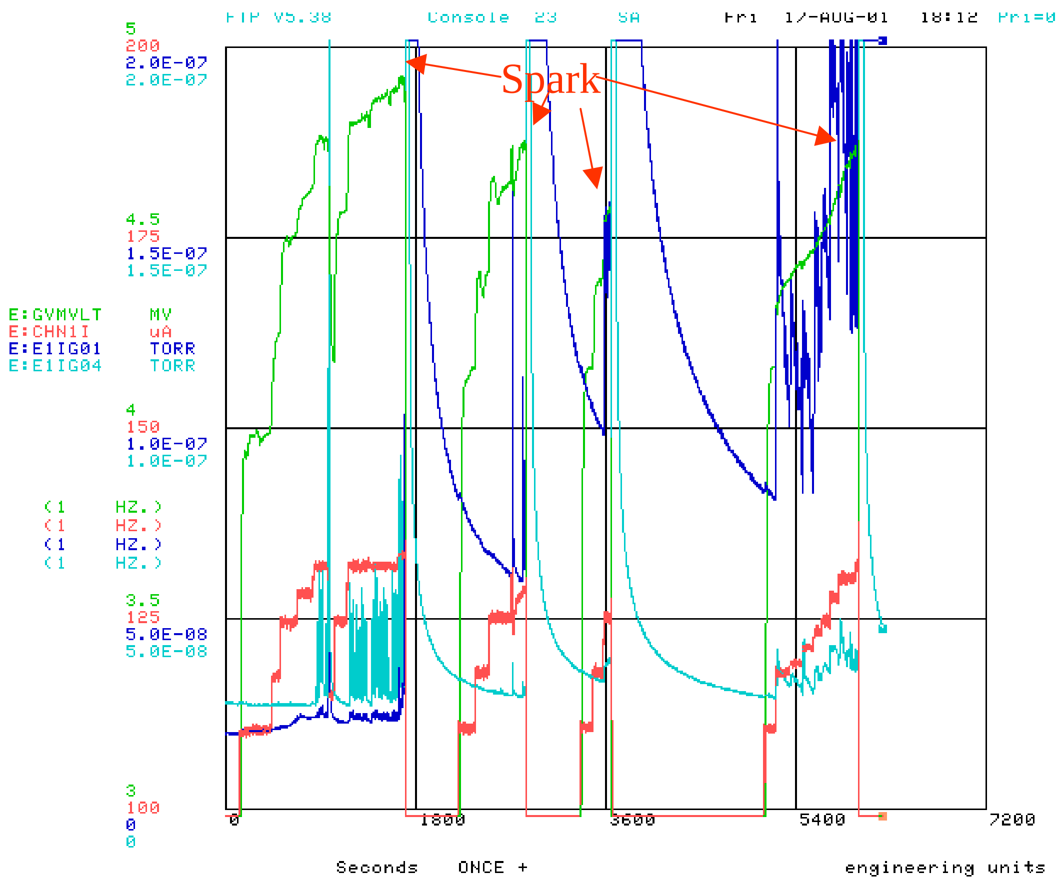
- Vacuum outgassing with beam
  - After all electronics is fixed and reliability is improved the rate of progress is determined by outgassing of the collector surface: initially the surface needed to be exposed to about 1 (mA/cm^2)-hour dose. At this dose, the outgassing rate drops to 10^{-3} molecule/electron -- acceptable for an operation with a 0.5-A beam current. The collector we are using now has been outgassed on a test bench and it was kept under vacuum. We anticipate this process to be less of a hindrance for us now.
- Beam physics
  - The final step of achieving a stable 500-mA would require good understanding of beam envelope, steering errors, and beam losses. In addition, we would like to test every type of diagnostics needed for the final system.

Notes on stability



1. A beam "crash" is a loss of beam recirculation, followed by a voltage drop.
2. A crash does not normally result in a pressure increase. The beam can be restored within one minute.
3. We do not yet understand the reason for such crashes.

An example of tube de-conditioning with sparks



E:GVMVLT: Pelletron voltage 3-5 MV. First, the max. voltage reached 4.9 MV.
After each spark the max voltage only got lower: 4.75 MV, 4.6 MV, 4.75 MV.

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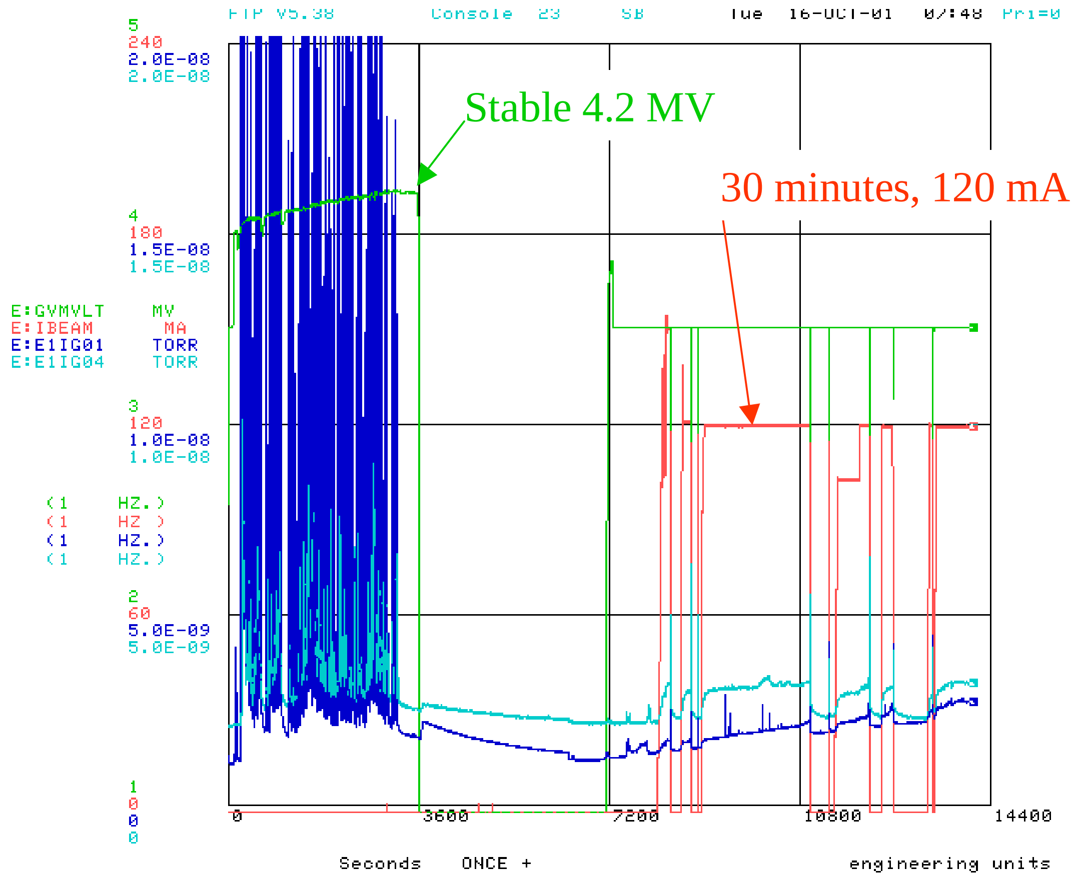
An example of tube conditioning and beam operation



E:GVMVLT -- Pelletron voltage 1- 5 MV.

E:IBEAM -- Beam current 0 - 240 mA.

Remarks about the current recirculation setup at Fermilab

- Our plan is to reach a stable 500 mA at 3.5 MV by the end of this calendar year. Also, we would like to demonstrate a high duty-cycle operation (90% or better) in a 24-hour period with currents above 300 mA.
- Tubes will have to be replaced sometime next year. The tubes will have to be baked and it will take several months to recover vacuum.
- We are planning to test every type of diagnostics on a short U-bend setup.
- We are also planning to perform tests on a slow beam position feed-back system. In the future full-scale beam line this will work together with the NMR-based magnet stabilization and the dispersionless beam transport line.

Summary of what has been accomplished in our recirculation test thus far

- Successfully bridged the NEC control system, supplied with the Pelletron, with Acnet. The machine is now 100% Acnet compatible and transparent.
- Electronics has been protected against sparks (Apr-July, 2001)
- Replaced mechanical hardware, damaged by sparks, with more robust components:
  - replaced: two damaged vacuum HV feedthrus; one beam-punctured bellows with a thick tube; one poisoned cathode; one damaged gun control (grid) electrode.
- Installed several levels of protection against beam-related full-tube breakdowns, which normally resulted in a tube de-conditioning (Aug, 2001):
  - A scraper in a high-dispersion position to absorb the beam during a crash.
  - A protection "box" that disables the beam if some parameter (i.e. HV) goes out of tolerance.
  - A software (slow) beam disable if the some Acnet parameters are out of tolerance
- Established a procedure for HV conditioning. Established a procedure for steering the beam into collector. Any crew member can now reach 100 mA in about one hour from scratch. Shift crews now work with three very different machine settings.
- Realized the significant role that ions play in beam stability (Oct 2001).

Beam transport line

- Angular momentum dominated beam transport
  - Beam transport optics from the exit of the gun solenoid to the entrance of the cooling section is dictated by three beam properties:

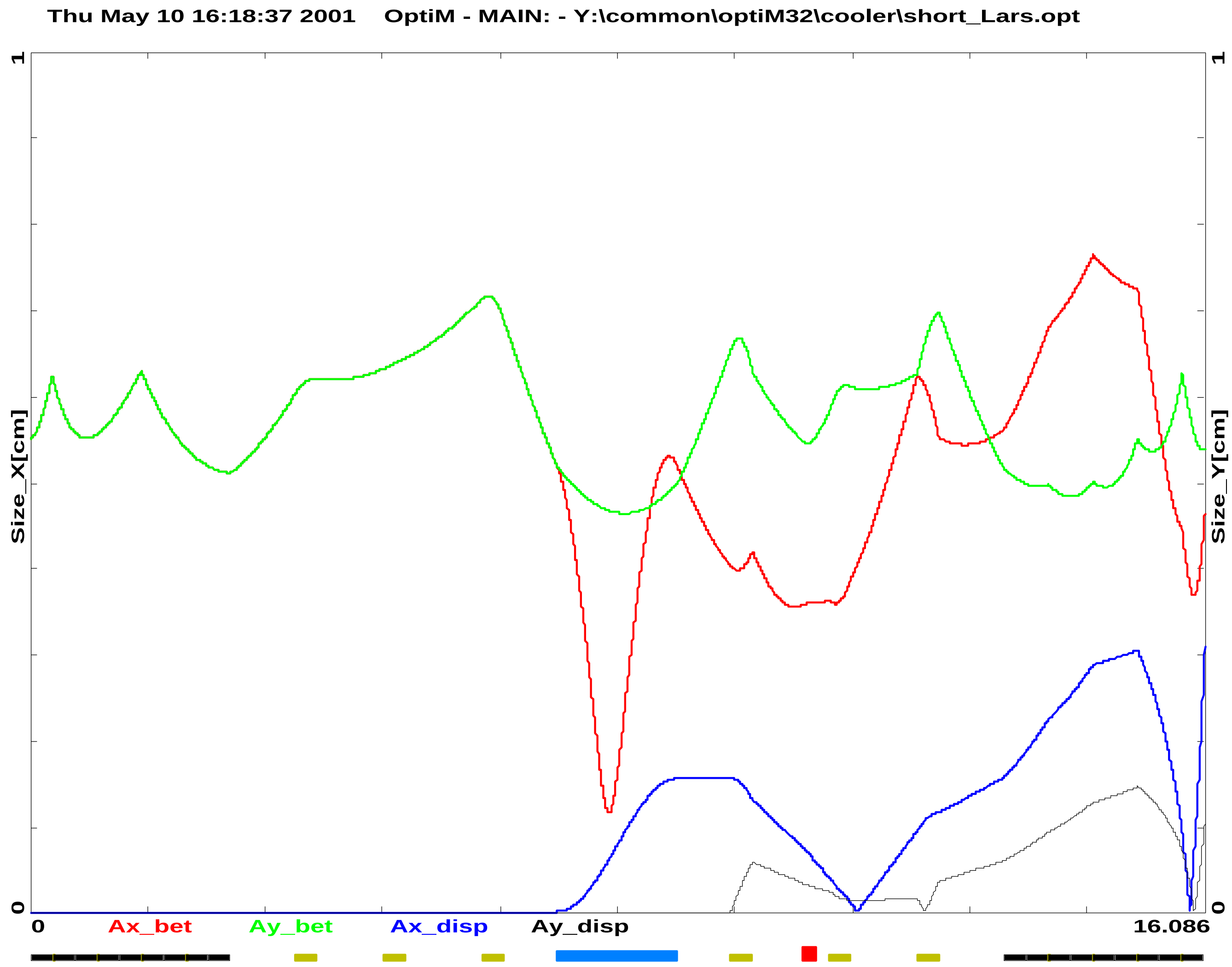
    (1) A large emittance-like contribution from the angular momentum

    $\varepsilon_N = eBr_c^2/(2mc^2)$. For $B = 600$ G, $r_c = 0.25$ cm, $\varepsilon_N \approx 100$ mm-mrad

    (2) Low beam aberrations

    (3) High optics stability and reproducibility
- A 5-mm diam cathode gun immersion in a 200-G solenoid was successfully tested in 1999. No difference in the Pelletron stability was observed.
- Beam line was fully designed and most of the elements were ordered.

Beam envelope in a short U-bend channel



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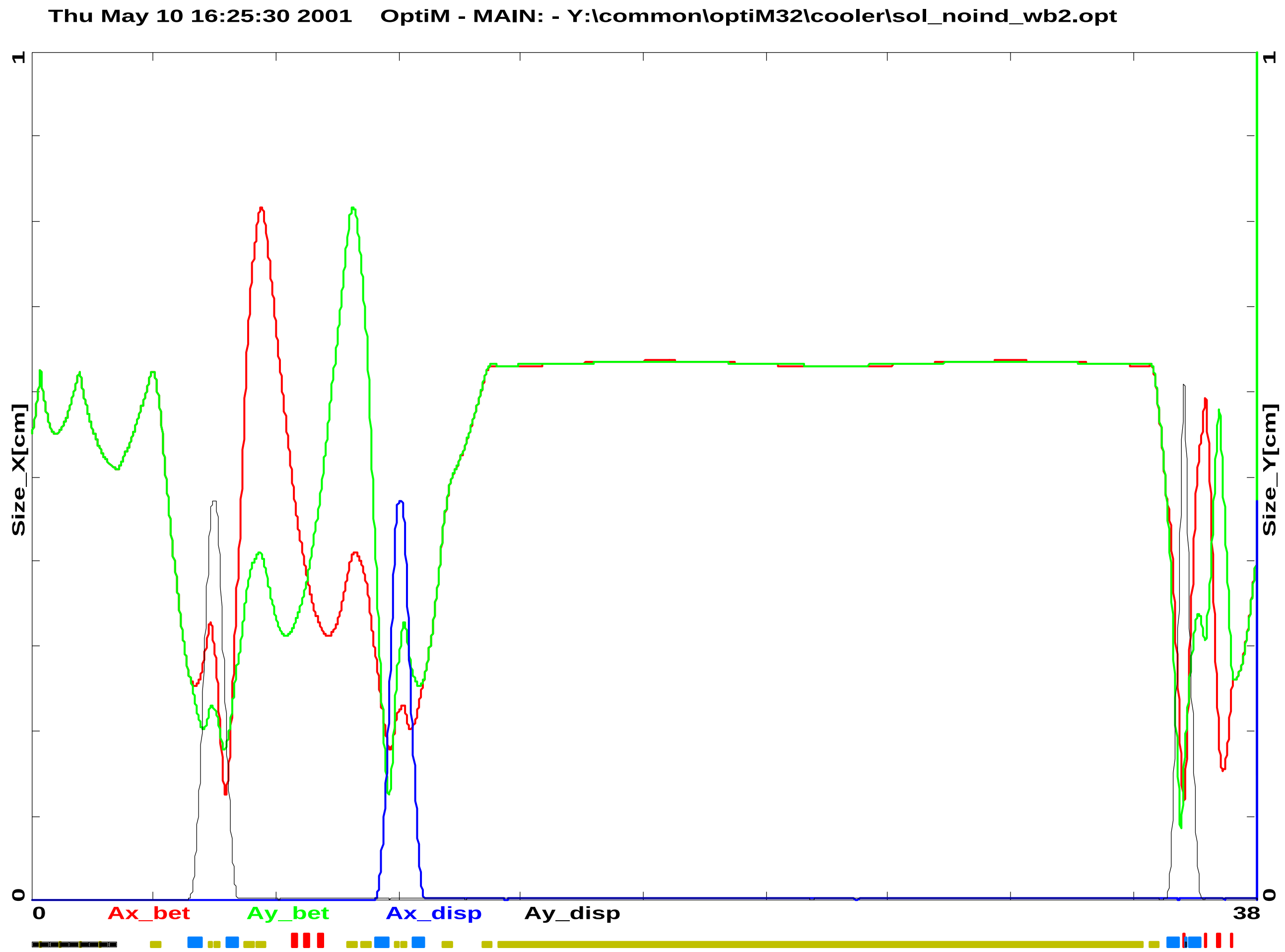
Beam envelope in a full-scale beamline



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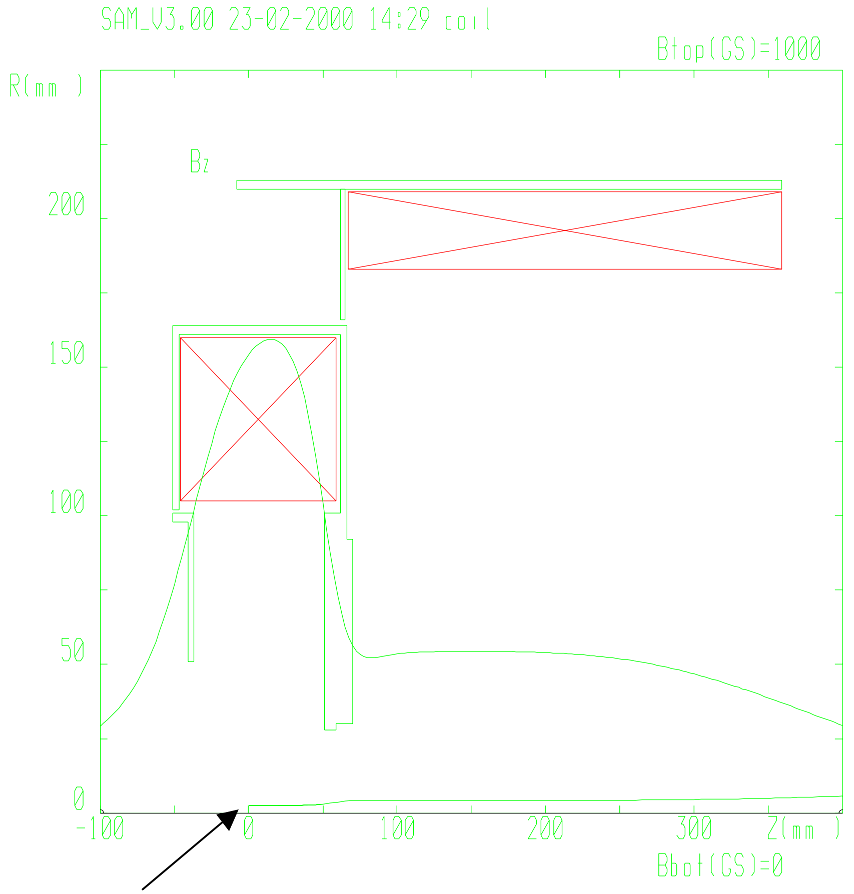
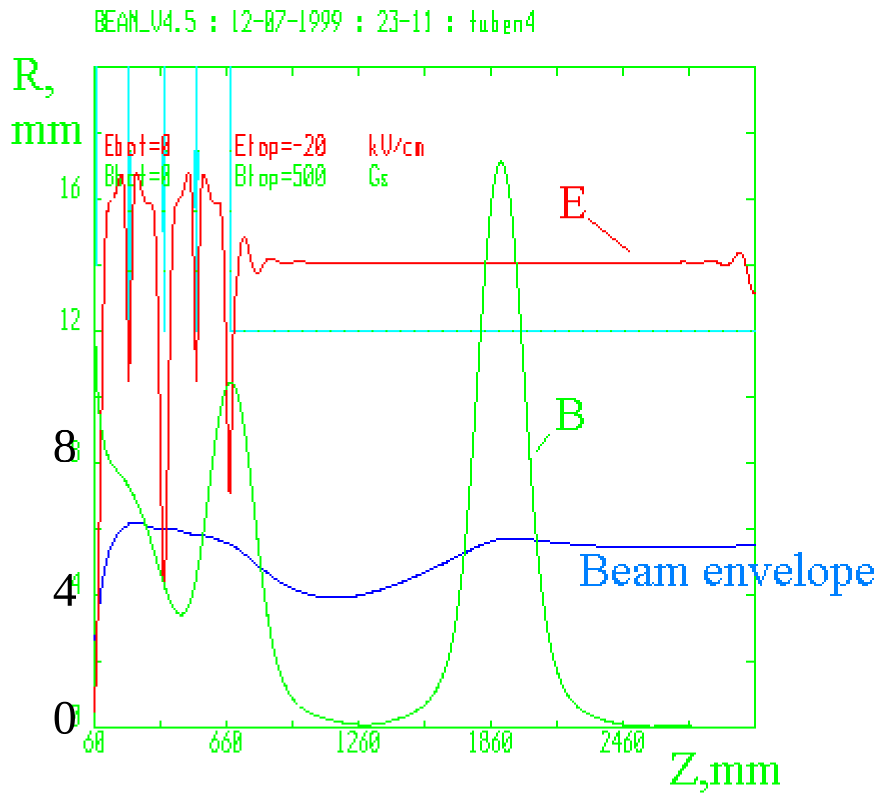
Magnetic field distribution in the gun



Cathode

Magnetic field at the cathode is 618 G.

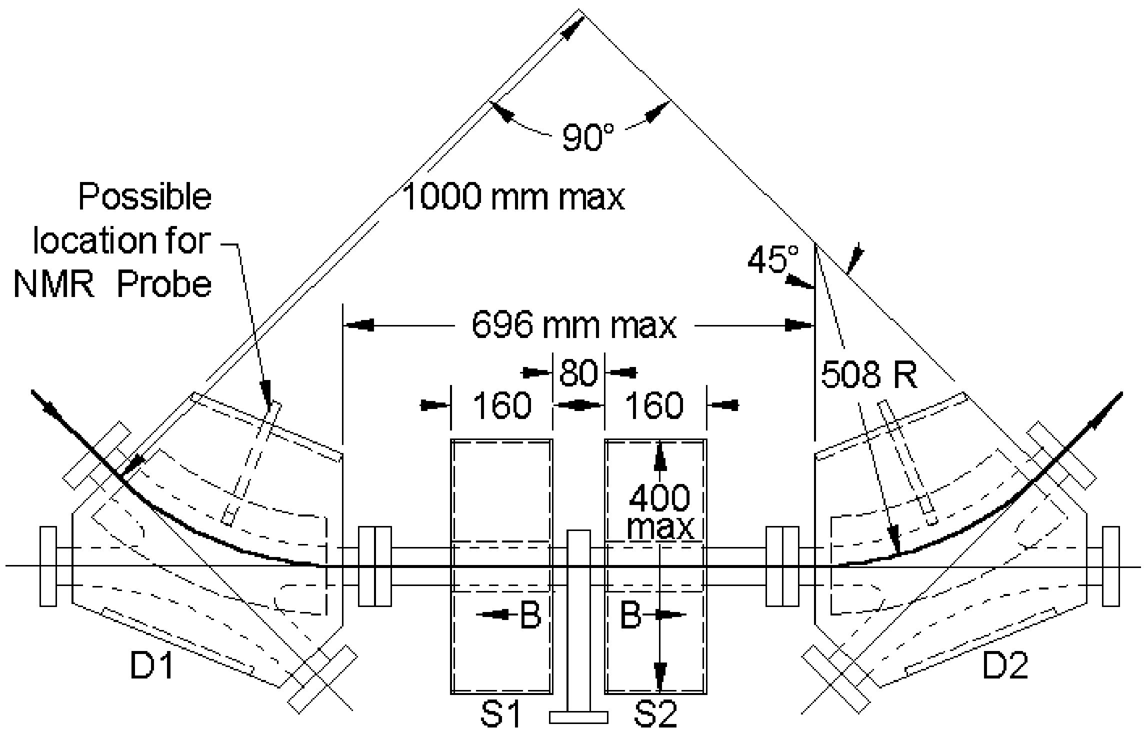
Beam envelope in the acceleration tube



Beam envelope simulation.

B_{cath} = 600 G, I_b = 1 A, U_0 = 4.3 MeV.

Beam line elements



A 90-degree dispersion-free bend is made of two NMR-regulated dipole magnets and two opposing-field solenoids. All mounted on an adjustable frame and shielded by a mu-metal shield. AL vacuum chamber will be used.

All bends are ordered and are due in Jan., 2002

Summary on beam line diagnostics

- BPM's: require a beam modulation at 25 kHz. Need accuracy of 50 μm (1 Hz BW) to measure electron and pbar positions relative to each other. Have seen a 0.2-mm noise level in a 100 Hz BW using a network analyzer. The electronics is currently being built by RFI and G. Saewert.
- Flying wire: we redesigned the Tevatron FW to use a non-magnetic rotary motion feedthru. Have not been tested yet.
- Scrapers: needed to determine the beam boundary. Several designs were tested. Found some problems, we'll continue to work on them.

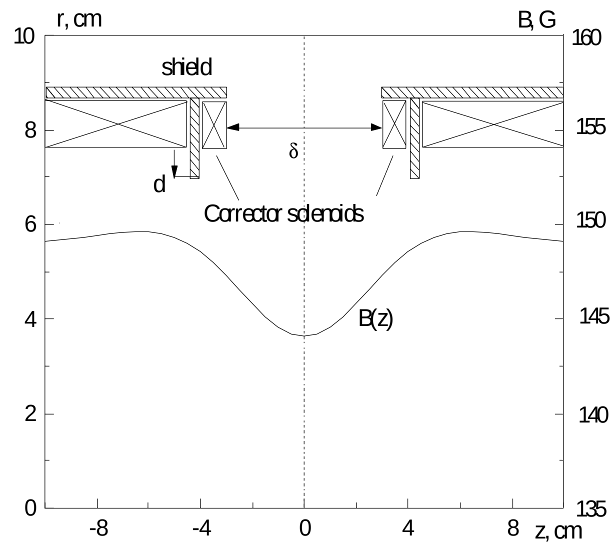
Cooling section solenoid

- consists of 10 identical solenoids in series, divided by instrumentation gaps

Total length	20 m
Magnetic field	50 - 150 G
Electron angles in the section	< 0.1 mrad
Integral of transverse magnetic field	≤ 0.3 G·cm

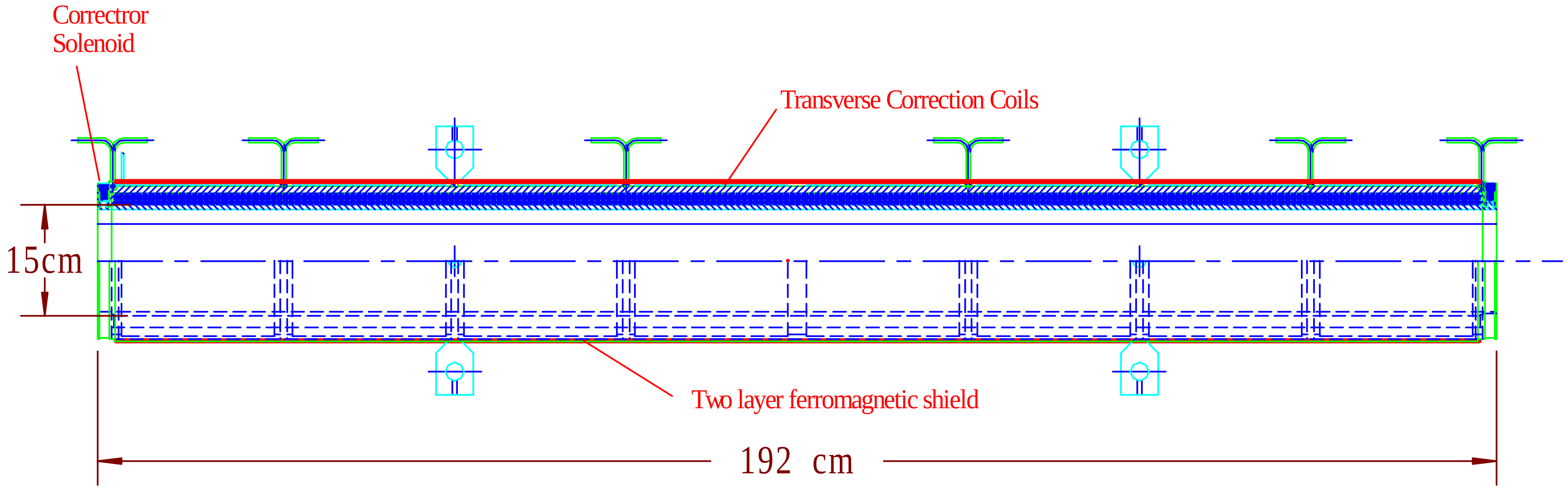
Solenoid Overview

- Ten 2-m long modules connected in series
- Each module:
  - a solenoid (188 cm long), 4 A, 80 V, 150 G
  - two corrector solenoids to correct gap effects
  - 20 transverse correctors (may be eventually connected in series with the solenoid PS)
  - 8-cm long gap for instrumentation
  - shielding with a coefficient of at least 1000 to shield stray fields of about 5 G.
- Two prototype modules were produced, installed and measured. Their properties were found satisfactory. The production of 12 more improved modules has started at Fermilab. The rate of delivery is expected to be 2 solenoids/month.



Parameters of the module solenoid

Number of layers	6
Number of turns in one layer	~980
Wire size (square AWG13)	1.88 mm
Current for B = 150 G	4 A
Total weight	250 kg
Power	240 W



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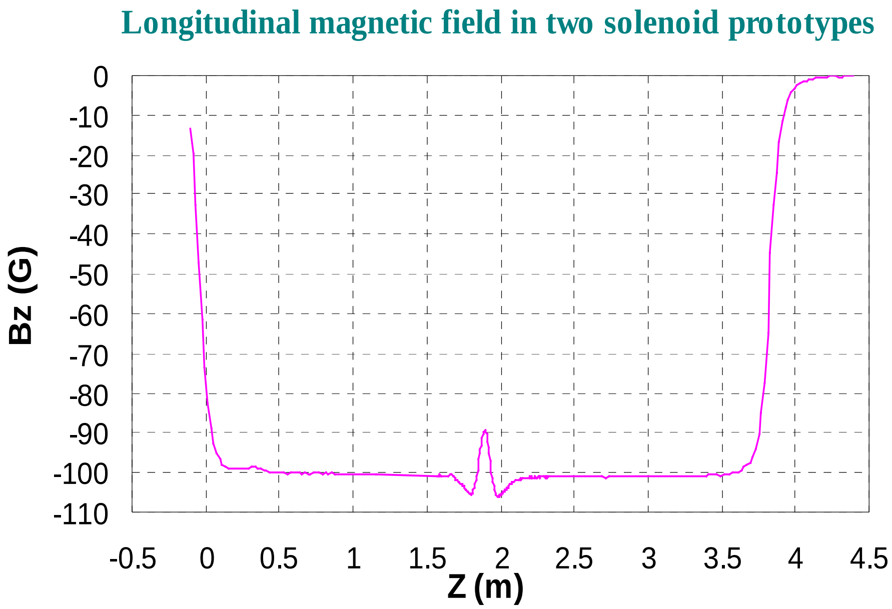
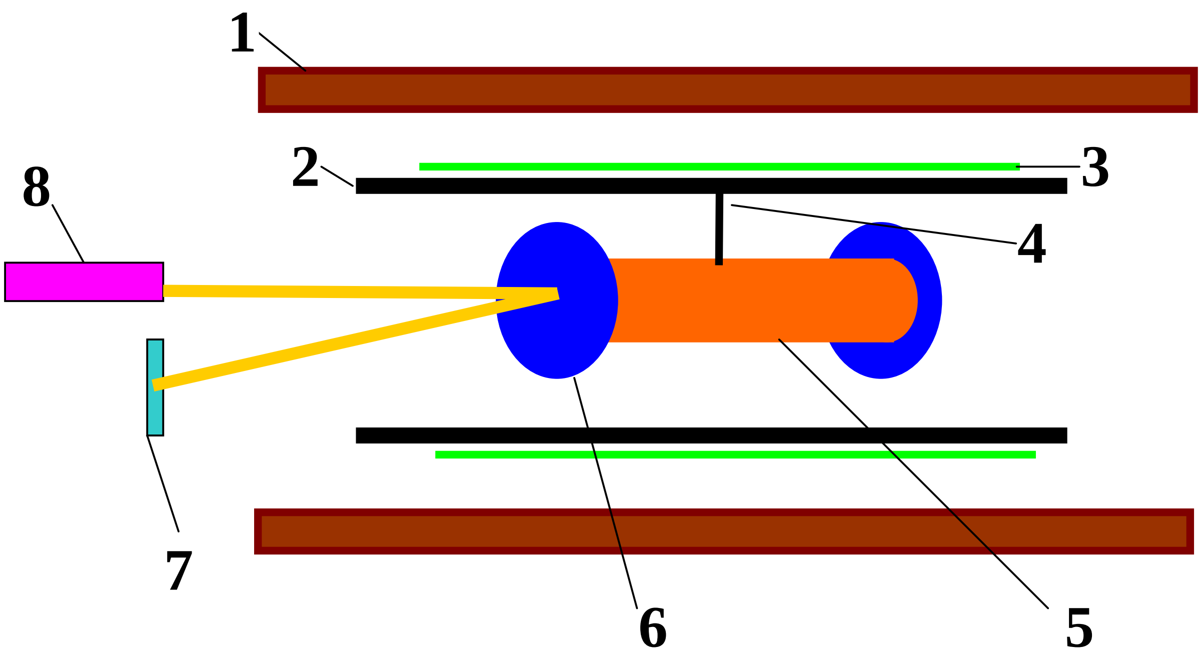
Two prototype cooling section solenoid modules installed



Compass-based magnetic field sensor (designed and built by Budker INP)



1- solenoid
2- cart
3- compensation coils
4- titanium 50 μm wire
5- permanent Nd-Fe-B magnet
6- mirror
7- position sensitive photodiode
8- laser

$$B_i(z) = B_z \cdot [\alpha(z)_i + \beta_i + \gamma_i] + [B_i^{earth}(z) + B_i^{shield}(z) + B_i^{sen}] + \delta B_i$$

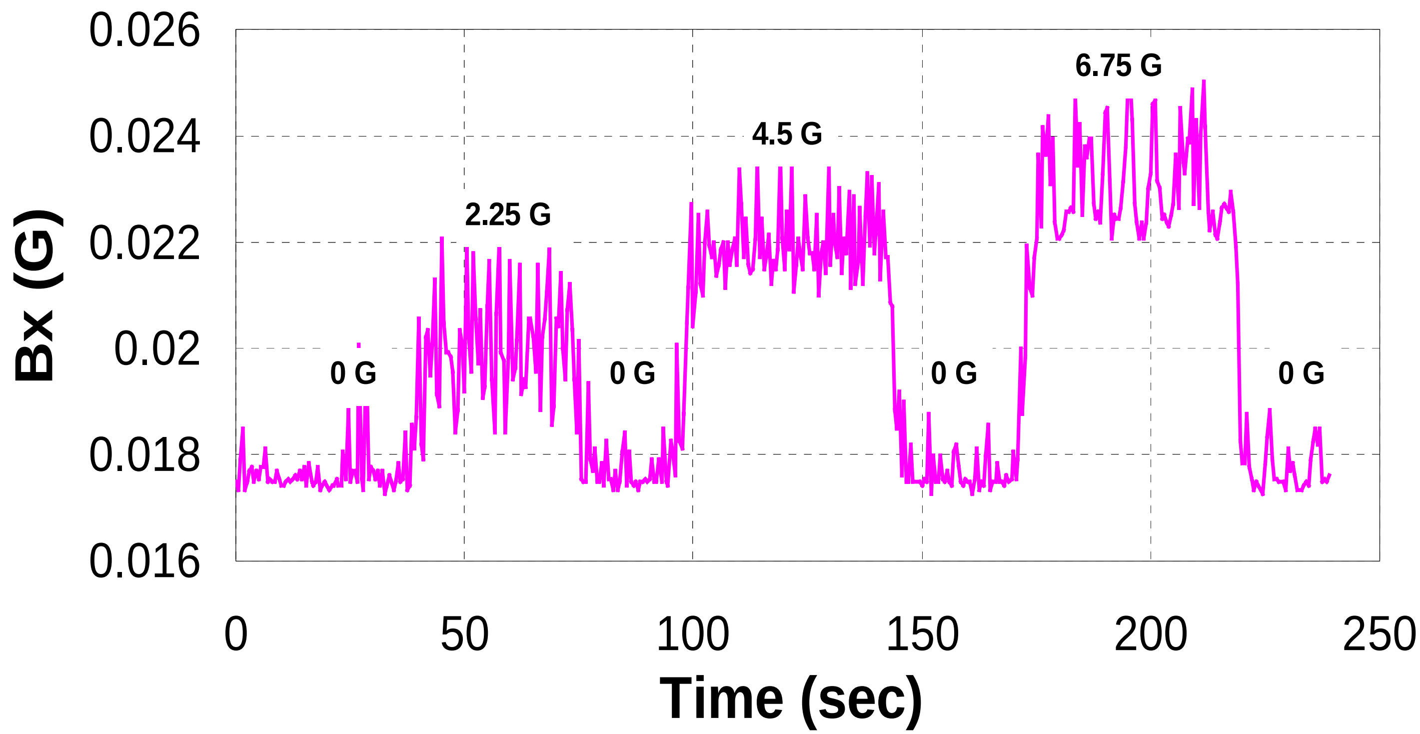
Field components, measured by the sensor

$$B_i(z) = B_z \cdot [\alpha_i(z) + \beta_i + \gamma_i] + [B_i^{earth}(z) + B_i^{shield}(z) + B_i^{sen}] + \delta B_i$$

Symbol	Origin	Typical value, in mG, at Bz = 100 G	Treatment
$\alpha_i(z)$	Errors of solenoid winding	50	Adjustment of dipole correctors
β_i	Average angle of a solenoid	100	Solenoid alignment
γ_i	Angle between the magnetic axis of the compass and normal to the mirror plane	1000 before correction, 100 after	Angle adjustment and measuring
$B^{earth}(z)$	External field	800 without shielding, < 2 with shielding	Magnetic shielding
$B^{shield}(z)$	Remnant field of the shield	5 ÷ 10	Shield annealing and careful handling; dipole correctors
B^{sen}	Sensor misbalance and elastic forces of the Ti wire	100	Balancing and measuring
δB	Noise of electronics, laser beam jitter, friction in the compass suspension	5	Improvement of apparatus; averaging

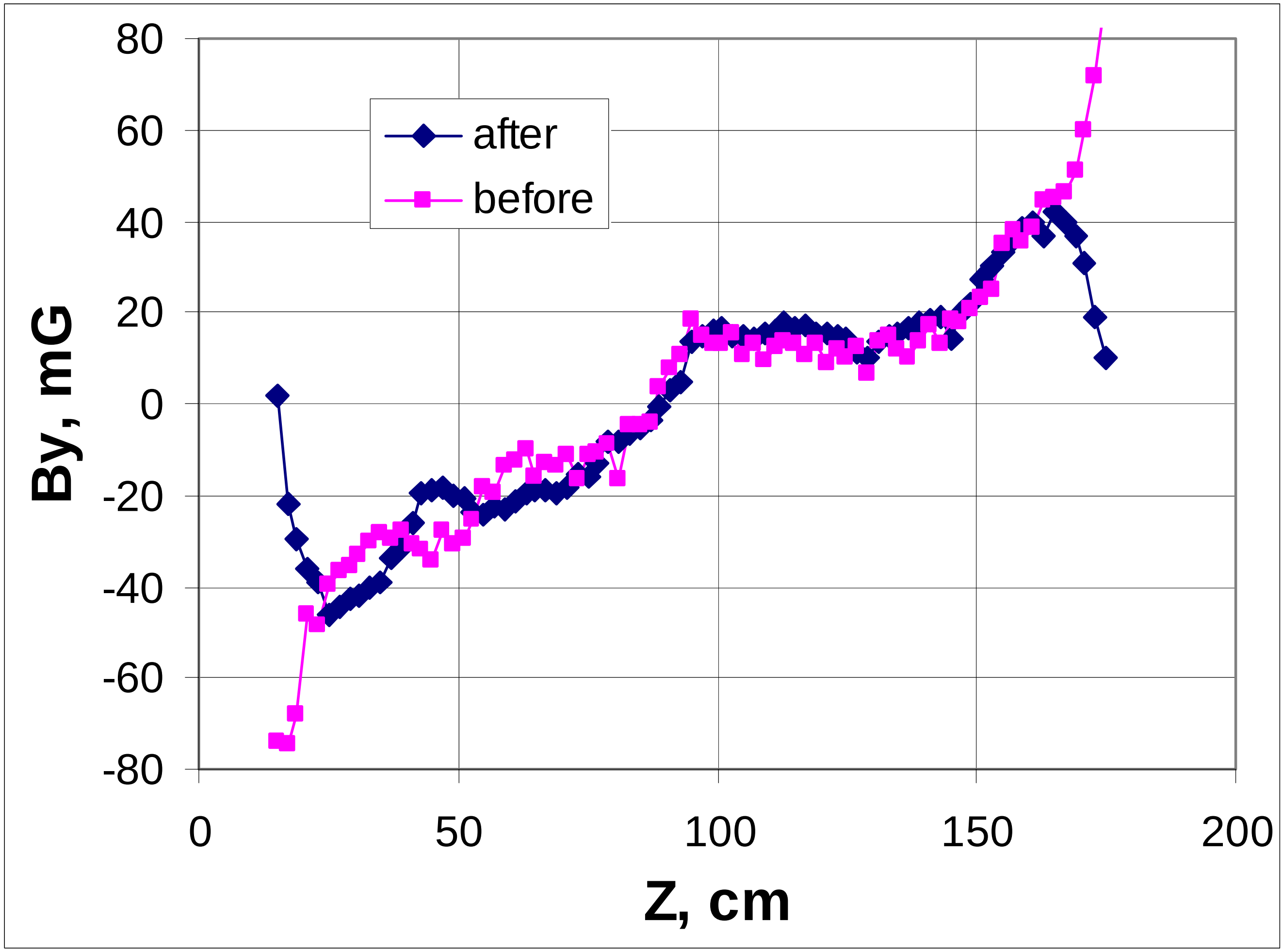
Shielding of external field.

Magnitudes of external fields with no shields are presented above the curve. Kx ~ 950.

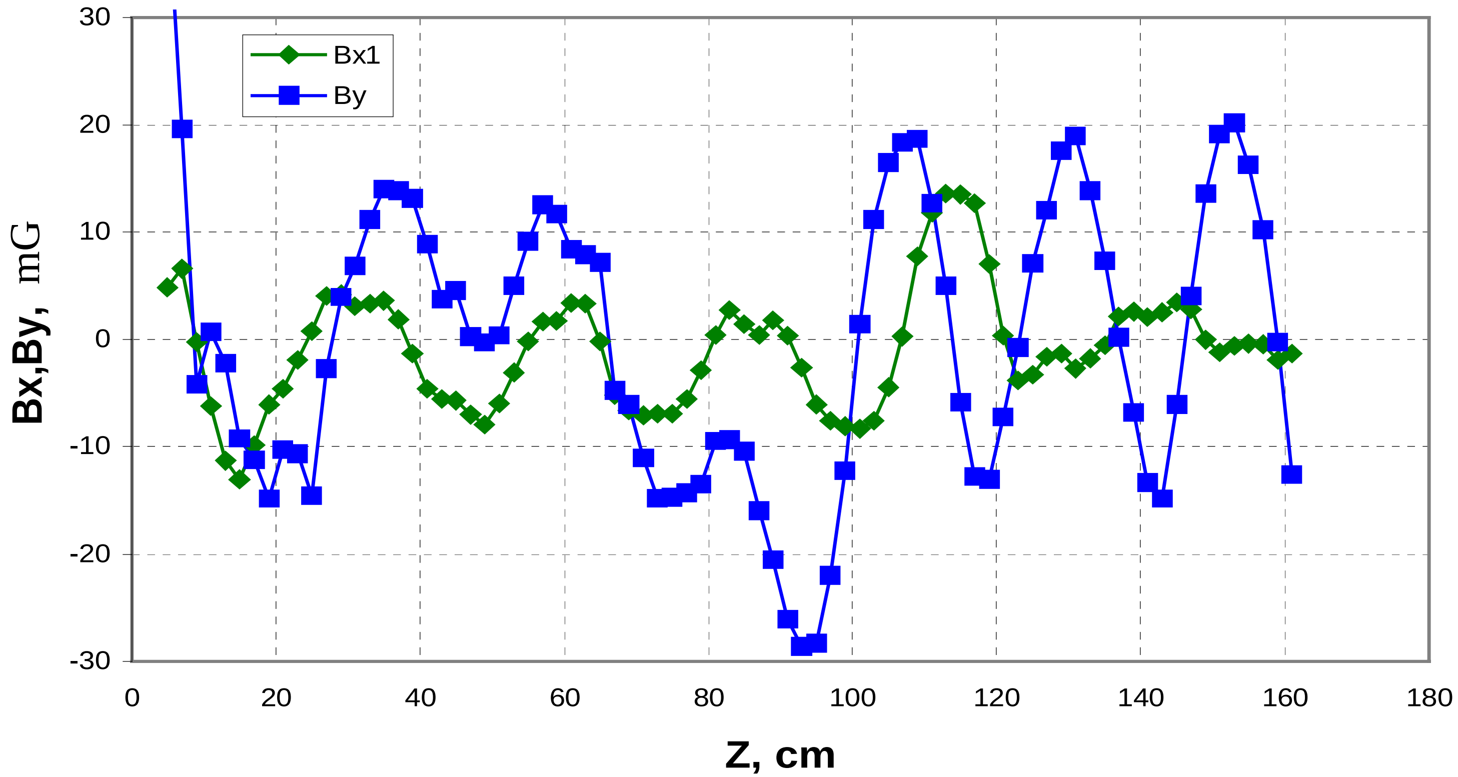


Component of the solenoid transverse magnetic field proportional to B_z

before and after solenoid rotation



Transverse magnetic fields in solenoid #1, Bz = 50 G
Correctors are set to minimize the transverse field integral, which is made less than 0.3 G-cm here.



Summary on the solenoid section

- 90% of all work has been done to understand the sensor performance and to make it stable and reproducible. This has now been achieved.
- The compass-based sensor can measure the solenoid transverse field with a relative accuracy of several mG. Absolute precision, determined by an angle between the magnetic axis of the compass and the mirror, is about 20 mG in a 100 G longitudinal field.
- Quality of measured solenoid prototypes is satisfactory for our purpose. Integrals of transverse fields can be made below 1 G·cm at the solenoid field of 150 G, if corrector currents are in optimum.
- Twelve new solenoids have been wound and epoxied by the TD. Two will be ready for installation after the shut-down.
- We are planing to have a shielding coefficient of 5000. Only two prototypes of this 3-layer design have manufactured but not tested. The remaining shields will be ordered after the shields are tested.

Electron Cooling Schedule (Tentative)

Project Milestone	Start Date	Finish Date	Duration
Commission U-Bend	3/01	12/01	10 months
500 mA, 1 hour		by 12/31/01	
FESS Title 2 begins		10/01/01	
Switch Over to Beamline	1/02	3/02	3 months
MI-31 bid out		02/01/02	
Commission Beamline	3/02	1/03	11 months
500 mA, 1 hour, beam properties		by 01/31/03	
Build MI-31 Enclosure	4/02	10/02	7 months
Push-Pipe	6/02	8/02	3 months
(Shutdown MI)	7/02	8/02	1 month ??
Disassemble @ Wideband	2/03	4/03	3 months
Install Pelletron @ MI-31	3/03	6/03	4 months
Shutdown MI	8/03	11/03	4 months
Install RR Components	8/03	10/03	3 months
Install Transferline	9/03	11/03	3 months
Commission E-Cool	12/03		

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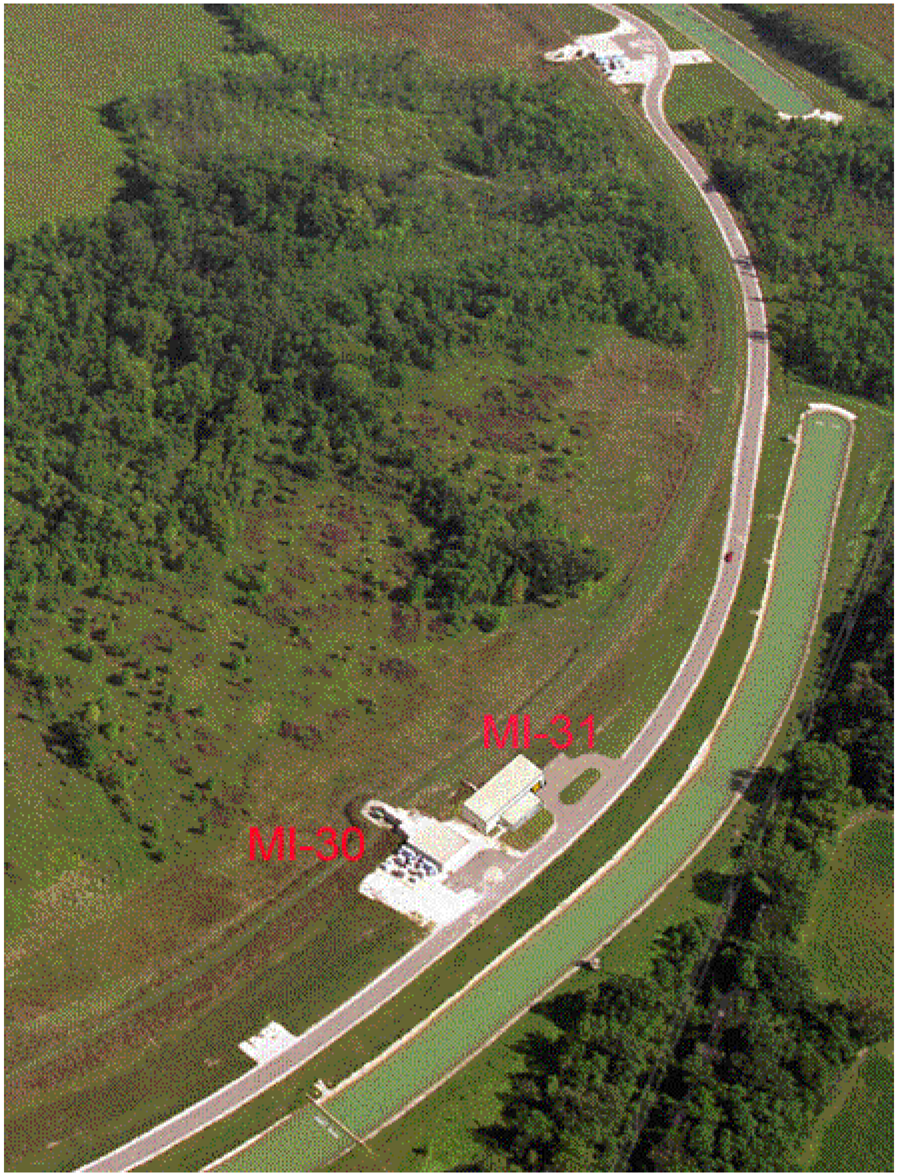

An artist's rendering of a proposed building (MI-31) next to the existing service building (MI-30).

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Electron cooling collaboration

- FNAL: S. Nagaitsev (group leader), A. Burov, A. C. Crawford, V. Dudnikov, T. Kroc, V. Lebedev, J. Leibfritz, J. MacLachlan, M. McGee, F. Ostiguy, G. Saewert, C.W. Schmidt, A. Shemyakin, J. Volk, A. Warner
- U. of Rochester: S. Seletsky (grad. student)
- CEBAF: Ya. Derbenev
- IUCF
- Budker INP
- JINR
- National Electrostatics Corporation